$$\lambda_1 = 2\frac{\sigma_x^2\sigma_y^2 - \rho_{xy}^2}{\sigma_x^2 + \sigma_y^2 - \left[\left(\sigma_x^2 - \sigma_y^2\right)^2 + 4\rho_{xy}^2\right]^{1/2}} \qquad \text{(A35)}$$

where σ_x^2, σ_y^2 and ρ_{xy} are elements of the Q (A18).

References

[1] Pinpoint's FCC License Application for the Array™ System in Dallas (2/9/93)

[2] Torrieri, Don J., "Statistical Theory of Passive Location Systems" IEEE Transactions on Aerospace and Electronic Systems VOL. AES-20, No.2 (March 1984)

[3] Foy, W.H., "Position Location Solutions by Taylor Series Estimation," IEEE Transactions on Aerospace and Electronic Systems VOL. AES-12, No.2 (March 1978)

[4] Marchand, N., "Error Distributions of Best Estimate of Position from Multiple Time Difference Hyperbolic Networks," IEEE Transactions on Aerospace and Navigational Electronics, VOL. AES-11 (June 1964)

[5] Lee, Harry, B. "A Novel Procedure for Assessing the Accuracy of Hyperbolic Multilateration Systems," IEEE Transactions on Aerospace and Electronic Systems VOL. AES-11 (January 1975)

[6] IEEE Transactions on Vehicular Technology VOL 37 No.1 (February 1988):20-21

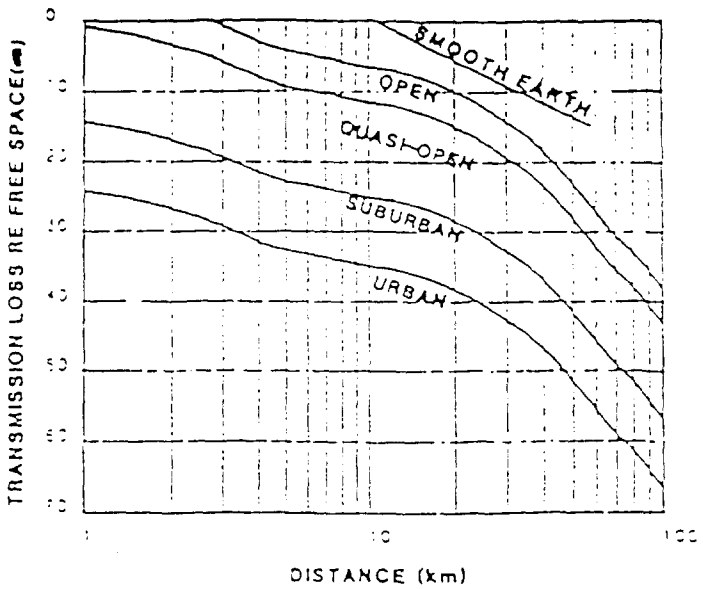
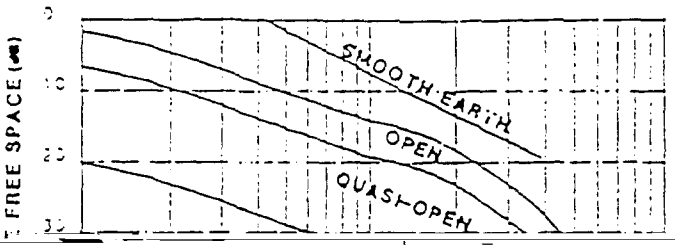


Fig. 1. Median transmission loss relative to the free-space transmission loss for Bullington smooth earth and Okumura urban, suburban, quasi-open, and open at 900 MHz; H_T = 500 ft (152 m); H_R = 6 ft (1.8 m).



THE ECONOMICS OF CO-CHANNEL SEPARATION FOR WIDEBAND PULSE RANGING LOCATION MONITORING SYSTEMS

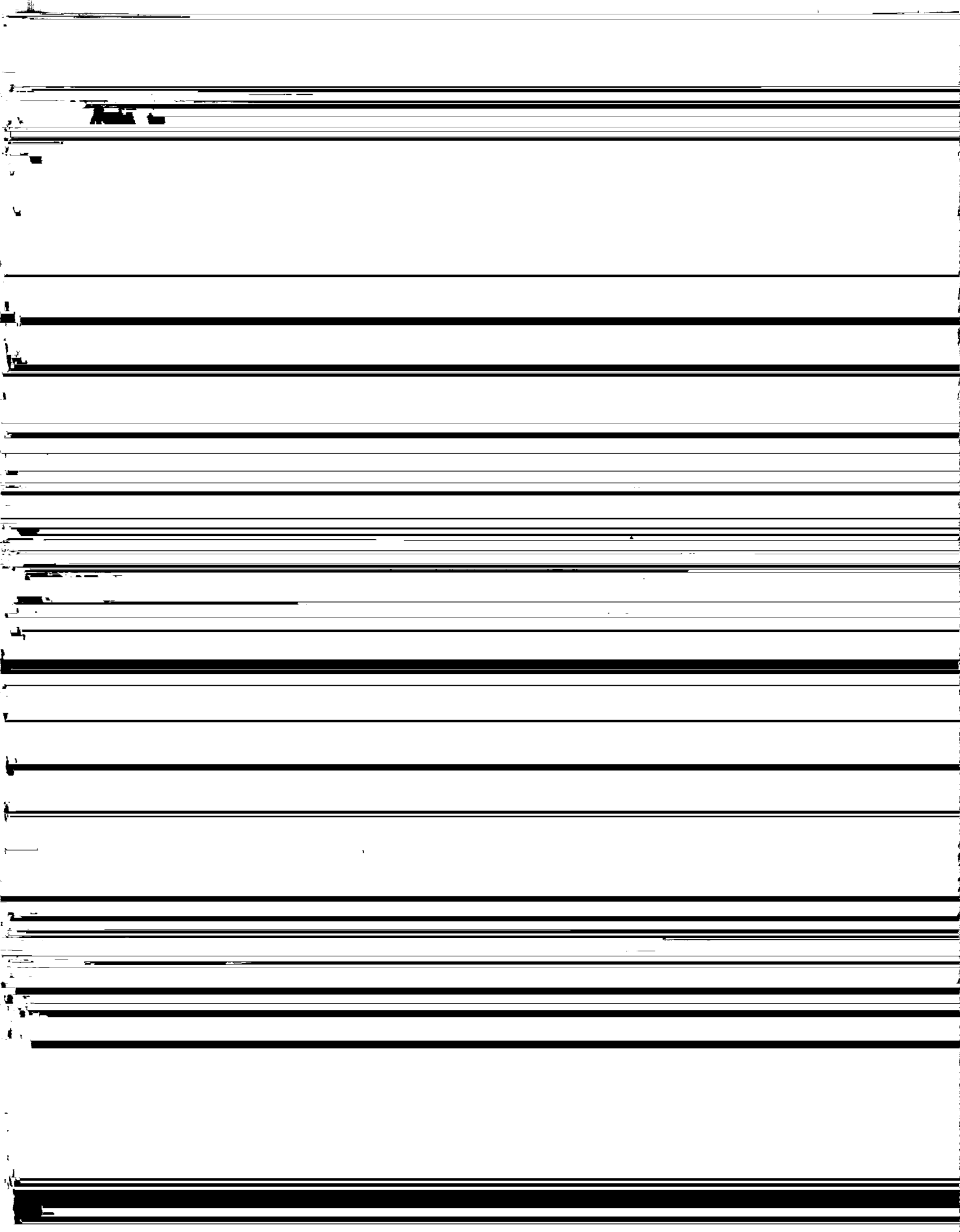
by

Richard Schmalensee
Gordon Y. Billard Professor of Economics and Management
Massachusetts Institute of Technology
Cambridge, Massachusetts

and

William E. Taylor
Senior Vice President
National Economic Research Associates, Inc.
Cambridge, Massachusetts

TABLE OF CONTENTS



multilateration systems and various types of narrowband systems and concludes that it is not reasonable or cost-effective for narrowband systems to share spectrum with wideband systems (¶ 14). Accordingly, the NOPR proposes that narrowband systems be required to move into the 902-904, 912-918, and 926-928 MHz bands, leaving two 8 MHz bands (904-912 and 918-926) to be used exclusively by WBPR LMS providers.[2] Narrowband LMS systems would be licensed on a non-exclusive basis with (i) no co-channel mileage separation requirements, (ii) coordination to be provided by the licensees and (iii) no restrictions on the number of such licenses (NOPR, ¶ 25). The NOPR seeks comment (¶ 22) on whether it is feasible for WBPR LMS systems to be licensed on a non-exclusive basis with no co-channel mileage separation requirements, though if spectrum sharing is not immediately feasible for these systems, current (or the first two applicants) licensees could be protected for five years.

Two controversial elements of the Teletrac proposal have important economic and public policy implications: (i) co-channel separation to minimize interference between different AVM systems and (ii) continuation of the assignment of 8 MHz to each system. To determine whether public policy is best served by open entry in the provision of WBPR LMS systems or by dividing the 8 MHz bands among additional competitors, it is important to compare the benefits of permitting and/or achieving entry by additional competitors with the costs of providing LMS services to customers in that environment. While one might expect some benefits from additional *competition*, it is not clear that an institutional arrangement that could lead to more

---

[2] ¶ 18 of the NOPR proposes that "only pulse-ranging LMS systems having a bandwidth of at least two megahertz be licensed in the 904-912 and 918-926 MHz bands."

II. BENEFITS OF COMPETITION

The NOPR thus perceives the benefits from having additional competitors in the LMS market to be lower prices for customers, more efficient use of the spectrum, and a faster rate of technical progress. Although competition can be expected to produce such benefits in most markets, it is unlikely that these desirable benefits can be achieved by operating the LMS markets on a shared basis.

A. Operation on a Non-Exclusive Basis will not Necessarily Cause the Number of Competitors to Increase.

Co-channel separation for WBPR LMS systems in the 900 MHz band will necessarily limit the number of such systems in any geographic area to two. Operating on a non-exclusive basis, on the other hand, would permit--but not guarantee--operation by more than two firms. Entry into these markets is voluntary, so it is reasonable to ask if the freedom for additional firms to enter each market is likely to result in a larger number of firms in each market.

1. Fixed Costs

In economic theory, the equilibrium number of firms in a market generally depends on the relationship between the minimum efficient scale of operation and the size of the market.[5] We discuss below two important sources of fixed costs in a WBPR LMS service: (i) the ordinary fixed costs of research and development and of transmission equipment and antennae sites, and (ii) the costs (measured in terms of

[5]For example, if economies of scale are important at levels of output of about half or a quarter of the market, then it will be difficult for the market to support more than one or two firms.

lost capacity) of synchronizing and calibrating the system. In addition, the capacity of two WBPR LMS providers sharing a given amount of spectrum is much smaller than that of a single firm using all the capacity. Thus rules which permit more firms to participate in a geographic market but which also increase the proportion of fixed costs

which minimizes the amount of coordination required among the competitors--subjects the firm to less uncertainty than other forms of sharing, particularly those that require rivals to cooperate and those that have not been tested in the field under commercial conditions.

3. Sunk costs of research and development

Compounding this problem is the fact that significant costs must be expended in the form of research and development or in licensing technology before a WBPR LMS firm can enter any geographic market. These costs are likely to be sunk: that is, the firm would be unable to recoup them if it subsequently left the market. Of course, a potential entrant must expect to be able to cover both its variable and fixed costs before it would voluntarily enter a market. Thus the fact that its cost per unit of capacity would be utterly unknown to it in a spectrum-sharing environment makes it unlikely that spectrum sharing would lead to a larger number of firms in the market.

Note that this effect is particularly important for WBPR LMS systems because the cost per unit of capacity for these systems in a shared environment depends on the number of competitors that declare an interest in being accommodated in the market, not the number of successful or active competitors. Suppose the city of Spokane were to be served by LMS suppliers on a shared basis. If five firms declared an intention to compete in Spokane, each firm would be limited to one-fifth the available bandwidth or one-fifth of the available time, regardless of the number of customers each firm serves. Hence a potential investor would have to be able to forecast the number of firms that would apply to serve Spokane in order to know the

unit cost of capacity (and the likely profitability) of the system that the investment in research and development would make possible.

B. Expanding the Number of Competitors Does Not Necessarily Reduce Price

Economic intuition sometimes suggests that the larger the number of independent firms supplying a service, the more competitive the market for that service will be. And as a consequence of such competition, price would be lower, service quality higher, and other economic characteristics of the market would be closer to those expected under conditions of effective competition. Several mechanisms have been suggested by which the greater number of competing firms translates into lower prices. First, the ability of each firm to affect market price is smaller the larger the number of (equal sized) firms in the market. If one duopolist reduces its output to raise the market price, the effect would be twice as strong as if one of four competitors reduced its output for the same purpose. Second, firms are sometimes thought to coordinate pricing and marketing decisions -- implicitly or explicitly -- and such coordination is simpler and more efficient the fewer the number of participants. It is easy to detect and punish cheating in a cartel of two or three firms; the problem is much more difficult in a cartel of ten. Many different models of oligopoly behavior exhibit this characteristic that the market price moves towards the competitive price as the number of competitors increases.[6]

---

[6]This intuition can be made more precise. In simple Cournot economic models of oligopoly, an increase in the number of firms in the market (all else equal) leads to a lower equilibrium price (see, e.g., J. Tirole, *The Theory of Industrial Organization*, Cambridge: The MIT Press, (1988), chapter 5). Indeed, if demand is a linear function of price and total cost is simply proportional to output, the market price is given by

In these models--and in the real world--these advantages from having additional participants in the market are quite sensitive to a number of assumptions.

1. Market demand is relatively elastic

The percentage reduction in market price from the presence of an additional firm depends on the market price elasticity of demand, which is defined as the percentage change in quantity elicited by a given percentage change in price. If demand is quite elastic, then the presence of an additional competitor has little effect on the market price because an increase in the quantity offered to the market has little effect on the equilibrium market price.[7] In Figure 1, market demand curve A

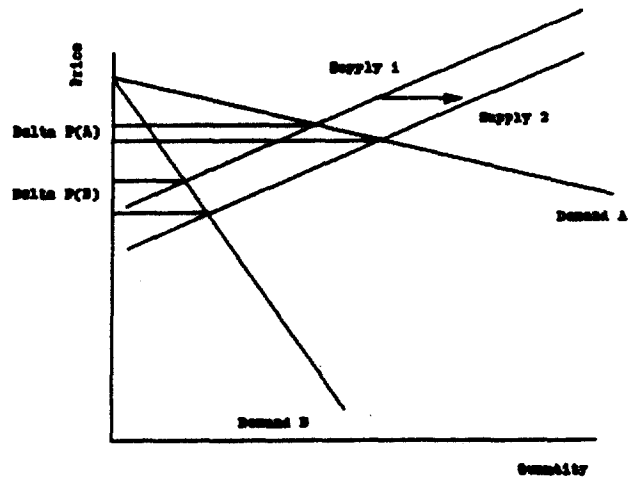
$$p = \frac{1}{n+1} \times [\, a + n\, c \,] \quad ,$$

where a is the market price at which demand is driven to 0, c is the constant marginal and average cost, and n is the number of firms in the market. As the number of firms becomes so large that no firm has any effect on the market price, market price will fall to its competitive level, (generally assumed to be the constant marginal and average cost of production), so that an average firm will not expect to make profits in excess of its cost of capital. If n equals 1, the market price equals the monopolist's profit-maximizing price (see, e.g., D.W. Carlton and J.M. Perloff, *Modern Industrial Organization*, New York: Harper Collins, (1990), p. 305). While the literal assumptions of the Cournot model appear quite restrictive, the Cournot outcome has been recognized in the literature as equivalent to a more realistic model in which firms determine their planned capacity in the first stage and then, in a second stage, compete by setting price given that fixed capacity (see, e.g., D. Kreps and J. Scheinkman, "Quality Precommitment and Bertrand Competition Yield Cournot Outcomes," *Bell Journal of Economics* Vol. 14 (1983), pp. 326-337). Such a model captures some important characteristics of WBPR LMS competition and embodies the intuitively plausible idea that when there are more uncoordinated competitors, market forces will work better to drive prices--and presumably other outcomes of competition--towards the desirable levels that would occur under open entry and effective competition. Other models of oligopoly which specify different reactions of competitors to changes in prices or quantities also exhibit this characteristic that the market price converges to the competitive price as the number of competitors becomes large. For example, the Stackleberg model of price leadership assumes that a dominant firm sets its profit-maximizing price under the assumption that a fringe of small competitors will take the dominant firm's price as given and maximize their profits. In the Stackleberg model, as the number of fringe firms becomes large, the market price falls to the competitive level of marginal cost.

[7] A new entrant shifts the market supply curve outward, i.e., at any given price, more output is offered to the market. The market price is determined by the interaction of the market demand and supply curves. If the market demand curve is more elastic (like A in Figure 1), the change in price associated with the shift in the supply curve is smaller ($Delta\ P(A)$) than the change in price that would occur if the market demand were the less elastic curve B.

little effect on the equilibrium market price.[7] In Figure 1, market demand curve A is everywhere more elastic than demand curve B. A new entrant shifts the market supply curve outward from *Supply 1* to *Supply 2*. The increase in quantity elicits a smaller change in market price for demand curve A (*Delta P(A)*) than for the less elastic demand curve B (*Delta P(B)*).

Figure 1
More Elastic Demand Leads to Smaller Price Reductions From Additional Entry



Under what circumstances can we expect the market demand for LMS services to be relatively price-elastic? The principle determinant of the market price elasticity of demand is the existence of products or services which substitute for some or all of the functions supplied by the service in question. Some LMS functions are already provided by similar services using different technology and different parts of the radio spectrum, as recognized by the Commission in its original 1974 Report and Order and again in the recent NOPR:

> "...there are a variety of different methods of locating vehicles including proximity sensing, mulitlateration and dead reckoning to serve the differing needs of users (NOPR ¶ 4).

---

[7] A new entrant shifts the market supply curve outward, i.e., at any given price, more output is offered to the market. The market price is determined by the intersection of the market demand and supply curves. If the market demand curve is more elastic (like *A* in Figure 1), the change in price associated with the shift in the supply curve is smaller (*Delta P(A)*) than the change in price that would occur if the market demand were the less elastic curve *B*.

For example, LoJack provides a stolen vehicle recovery service that uses direction-finding equipment in police cars to track signals emitted by hidden transmitters in stolen vehicles served by the LoJack system. The technology is very different from that of Teletrac and LoJack does not use spectrum in the 900 MHz band. Nonetheless, from the perspective of a customer, LoJack and Teletrac both provide stolen vehicle location services.

In addition, other technologies can be used to provide particular LMS services in particular situations. In geographic areas having a clear view to the sky, satellite-based location systems such as the Global Positioning System, Private Satellite and Low Earth Orbit Satellites can provide very accurate tracking of moving objects including corporate fleets of vehicles over a wide area.[8] Cellular mobile telephone and PCS systems can supply some of the safety and ancillary communications features provided by some LMS offerings. Teletrac's WBPR LMS technology may have some cost and quality advantages over competitors for some services, but the presence of these competitors, using different technology and different parts of the spectrum[9] means that customers have a choice of suppliers for these services regardless of the number of firms that eventually produce WBPR LMS services in the LMS band.

---

[8]Indeed, such systems have been available in the market for at least a year. Trimble Navigation Limited has offered a GPS-based tracking, dispatching, and delivery service called FleetVision™ in Los Angeles since April 1992 that duplicates many of the features of Teletrac's fleet monitoring service.

[9]The NOPR recognizes that the frequency band 2450-2483.5 MHz "is available for narrow-band [LMS] systems and many are already designed to use that band" (¶ 18). Similarly, ¶ 27 points out that spectrum below 512 MHz is available for LMS services. Finally, the Notice of Proposed Rulemaking in the PCS docket proposes to allocate the 1910-1930 MHz band to unlicensed PCS operation.

For these reasons, market demand is likely to be quite elastic for LMS-type services. The defining function that LMS supplies--monitoring the location of vehicles or objects--is not one that all business or residential customers require at any price. In contrast, both business and residence customers require basic access to the telephone network, and where there are no substitutes for the local telephone company's basic service, the price elasticity of demand for basic access is quite low. While a measurement of the price elasticity of demand for LMS services is beyond the scope of this study,[10] the number of substitutes and the attributes of the service suggest that its price elasticity is greater (in absolute value) than that of basic access to the telephone network or of cellular mobile telephone service. Thus the gains from having more than two competitors in the 900 MHz band in each WBPR LMS market are likely to be small (relative to the cellular case) if there were two WBPR LMS systems in each market.

2. The models assume pricing behavior is uncoordinated

Another important assumption of the model is that pricing behavior is uncoordinated. In a Cournot model, each firm takes its rivals' output or capacity as fixed and sets its price so as to maximize profits. If the presence of multiple firms in the market requires extensive coordination to make competition feasible, the assumption of independent price and quantity decisions among the rival firms is unrealistic, and the reduction in price from an additional competitor will be smaller

[10]It is very difficult to estimate the price elasticity of demand for a new and growing service. The principle difficulty is that since the service is new, there are not much available data. Moreover, the price and quantity combinations that are observed cannot be presumed to lie on a single, constant demand curve, so we cannot learn about the slope and elasticity of demand from historical data.

than the model would predict. Moreover, it is more difficult to coordinate (i) four firms sharing spectrum in a geographic market compared with three and (ii) firms using different technologies providing different services. As long as coordination is required to share spectrum in a given geographic market, it is unlikely that the full benefit of vigorous price or product competition would emerge from the presence of additional competitors. Other oligopoly models (e.g., the contestable markets model), rely on open entry and the absence of entry barriers to drive market price down to its competitive level. If the technology for time-domain or frequency-domain sharing requires coordination among a known number of firms, then at any point in time,

systems, the cost of coordinating spectrum sharing and the dependence of unit capacity costs on the number of competitors would have to be small. Costs of uncertainty are ignored in these models, in particular, the uncertainty in WBPR LMS systems in a shared environment associated with having to accommodate an unknown number of firms in the market or having to modify a system or a sharing arrangement whenever an additional entrant appears on the scene.

4. Summary

Economic analysis does not imply that the market price would be lower in a WBPR LMS geographic market having four suppliers rather than two. There cannot be much additional price reduction that could be achieved, since the LMS market demand curve is relatively elastic, because there are many substitutes for these services. The reduction in the ability to collude that might stem from having additional competitors is mitigated by the additional coordination that would be necessary to implement time or frequency sharing for these services, assuming that such coordination were even feasible. Finally, there are substantial increases in average cost associated with spectrum sharing for these services. Thus even if price were driven towards cost by the additional competition, because entry raises every firms' unit capacity costs, price would not necessarily fall from its current level.

C. Expanding the Number of Competitors Will Not Result in More Efficient Spectrum Use.

Providing WBPR LMS services in the manner which most efficiently uses the scarce resource of spectrum is one in which the greatest number of subscribers can be

served in a market for a given allocation of bandwidth. It is sometimes thought that competition can increase spectrum efficiency in several ways.

1. Expansion of market demand

Competition is thought to have two distinct effects on the level of market demand. To the extent that the presence of more competitors lowers the market price, more customers will find it attractive to subscribe to the service. Alternatively, the presence of robust competition could lead to advertising, improvements in quality, and the development of new services, all of which would increase the amount of the service demanded at any given price. That is, output could increase by moving down the market demand curve or by shifting the market demand curve outward.

As shown in the previous section, the presence of more competitors in each LMS market will not necessarily reduce the market price by a significant amount. Thus the market stimulation derived from a reduction in price caused by additional competitors in each LMS market may not be significant. Other firms produce substitutes for functions of LMS services, so expansion in demand will depend on the competition among different services and technologies rather than simply among the 8 MHz WBPR LMS services produced in the 904-912 or 918-926 MHz bands.

In addition, even if provision is made to accommodate more competitors in the 904-912 or 918-926 MHz bands, the increase in the number of competitors does not necessarily lead to an expansion of the market. As we discuss below in Section III, as more firms share a fixed amount of frequency, the total number of customers that can be served by all firms together *falls*. Hence while more robust competition

can lead to an expansion of demand, achieving robust LMS competition through an increase in the number of competitors can lead to a contraction in the amount of service, in total, that can be supplied.

Finally, the presence of fixed costs--either capital equipment (towers and antennae) or bandwidth that must be used for synchronization and calibration--means that a larger market achieved by increasing the number of competitors will not--in general--lead to a more efficient use of the spectrum. The presence of four competitors instead of two may lead to a market price reduction, an associated stimulation of demand, and an outward shift in demand due to additional marketing or advertising, but the question for first-order (or technical efficiency) is whether or not cost per subscriber is lower in the four firm scenario. We discuss below the significant additional costs that sharing time or sharing frequency between two competitors requires.

2. Static efficiency: conservation of bandwidth

It is sometimes argued that competition and sharing may force the firm to

has nearly the same incentive to minimize cost regardless of the number of firms in the market.[12] Every dollar that the monopolist can save by controlling costs increases profit by a dollar, and a firm in a competitive market perceives precisely the same tradeoff. Hence, given the technology, there is no reason to think that a monopolist will have higher costs at any point in time than a firm in a competitive market.

3. Dynamic efficiency: research and development

However, the technology is not necessarily given; firms invest in research and development to create new technology, and it may be the case that the structure of the market and degree of competition affects the rate at which firms perform research and development and invest in future cost reductions. However, again, the economics literature provides little unambiguous support for this view. Beginning with the work of Joseph Schumpeter,' economists have examined models linking firm size, market structure and the rate of technical innovation. In Schumpeter's view,

> "the atomistic firm operating in a competitive market may be a perfectly suitable vehicle for static resource allocation, but the large firm operating in a concentrated market was the 'most powerful engine of progress and ... long-run expansion of total output' "[13].

Driving this opinion was the recognition that firms required some expectation of (at least) transient market power in order to have any incentive to invest in research and

---

[12]The only differences in incentives to minimize costs stem from the lower level of demand produced by a monopolist and the smaller (in absolute value) price elasticity of demand that a monopolist faces.

[13]W.M. Cohen and R.C. Levin, "Empirical Studies of Innovation and Market Structure," in R. Schmalensee and R. Willig (eds.), Handbook of Industrial Organization, Vol. 2, New York: North-Holland, (1989), p. 1060, citing J. Schumpeter, Capitalism, Socialism, and Democracy. New York: Harper, (1942), p. 106.

development. In addition, this view recognizes that research generates many externalities and that a monopoly market structure permits the investing firm to appropriate a larger portion of the benefits of research than a more competitive market structure.

Under different circumstances, other theoretical economic models generate the opposite conclusion. Suppose a firm is deciding whether to undertake a particular research project that will lower costs, and it believes that if it does not successfully pursue the project, no other firm will. In this case, the firm will have a higher incentive to invest in such research if the market structure is competitive than if its monopolized, because the higher output of the competitive market means that profits from cost reduction will be larger.[14]

The empirical literature in economics similarly provides little support for the view that an increase in the number of firms in a market necessarily increases the amount of investment in research and development or the rate of technological progress. The majority of studies (but by no means all) concerning the relationship between market concentration and R&D activity show a positive association,[15] some have shown a negative association,[16] and some show the relationship to be an

---

[14]See K.J. Arrow, "Economic Welfare and the Allocation of Resources for Invention, " in Universities-National Bureau Committee for Economic Research, *The Rate and Direction of Inventive Activity*, Princeton: Princeton University Press, (1962).

[15]e.g., E. Mansfield, *Industrial Research and Technological Innovation: An Econometric Analysis*, New York: Norton, 1968, and F.M. Scherer, "Market Structure and the Employment of Scientists and Engineers," *American Economic Review*, Vol. 57, (1967), pp. 524-531.

[16]e.g., O.E. Williamson, "Innovation and Market Structure," *Journal of Political Economy*, Vol. 73, (1965), pp. 67-73.

"inverted U": i.e., research activity increases with market concentration up to a point after which it decreases.[17] Additional empirical results suggest that a component of the causal relationship between market structure and research intensity goes the other way: that high rates of research and development leads to markets with higher concentration.[18] Some evidence suggests the reverse: if innovation occurs disproportionately among smaller firms in the industry increased innovation will reduce market concentration.[19]

Whether or not higher market concentration is associated with higher research and development intensity, the empirical literature suggests that the effect of market structure is small. Market concentration contributes little to an explanation of the variance of research and development across industries compared with demand effects, research opportunity differences, and appropriability differences:

> "...these results leave little support for the view that industrial concentration is an independent, significant, and important determinant of innovative behavior and performance."[20]

Moreover, there is at least one difficulty in applying this body of economic evidence to the WBPR LMS markets. The relationship between research intensity and market structure is not even relevant to the public policy case at issue unless it follows

---

[17]e.g., Scherer, op. cit., R.C. Levin, W.M. Cohen, and D.C. Mowry, "R&D Appropriability, Opportunity, and Market Structure: New Evidence on Some Schumpeterian Hypotheses," *American Economic Review Proceedings*, Vol. 75 (1985), pp. 20-24.

[18]e.g., R.C. Levin and P.C. Reiss, "Tests of a Schumpeterian Model of R&D and Market Structure," in Z. Griliches (ed.), *R&D, Patents, and Productivity*, Chicago: University of Chicago Press, (1984).

[19]See W.M. Cohen and R.C. Levin , op. cit., pp. 1075-1076.

[20]W.M. Cohen and R.C. Levin, op. cit., p. 1078.

that issuing non-exclusive WBPR LMS licenses will necessarily result in lower market concentration in a relevant economic market. There are many WBPR LMS markets in the United States (not to mention abroad) and technical innovations in WBPR LMS technology apply instantly and costlessly to every market. Thus the number of WBPR LMS service suppliers in any single geographic market has even less bearing on any firm's incentive to innovate than it does in the economics literature which assumes all firms that perform R&D compete in the same product market. Research and development in telecommunications markets is not performed exclusively--or even predominantly--by service providers. The concentration of different geographic WBPR LMS service markets has nothing to do with the supply of research and development to those markets. Thus, the conclusion from economic theory and a generation of empirical studies is that there is little theoretical or empirical evidence to suggest that the presence of additional suppliers in a WBPR LMS market will induce more rapid technological change.

Finally, issuing non-exclusive licenses has other[21] effects on the incentive to engage in research and development that operate through mechanisms other than